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RESEARCH MEMORANDUM

INVESTIGATION OF EFFECTS OF GRAIN SIZE UPON ENGINE LIFE OF CAST AMS 5385 GAS TURBINE BLADES

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
July 6, 1953

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INVESTIGATION OF EFFECTS OF GRAIN SIZE UPON ENGINE LIFE OF CAST AMS 5385 GAS TURBINE BLADES

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SUMMARY

An investigation was conducted at the NACA Lewis laboratory to: (a) determine the effects of pouring temperature and grain size upon uniformity of lives and initial failure times of groups of experimentally cast AMS 5385 gas turbine blades aged 24 hours at 1350° F; and (b) relate individual lives of these experimentally cast blades to grain size.

Grain size varied from 4 to 11,200 grains (A.S.T.M. 8) per blade cross section (area of 0.035 sq in.), and was achieved primarily by variation in pouring temperatures. The performance of the experimental blades was compared with the performance of commercially produced AMS 5385 blades. The blades were operated at a temperature of 1450° F and a midspan stress of 19,000 pounds per square inch in a small gas turbine. A total of 90 blades were investigated.

The results of this investigation are as follows:

1. A correlation was found to exist between number of grains per blade cross section and blade life for the experimentally cast blades; longer life was associated with the coarser grain sizes.

2. The initial failure time and uniformity of life was better for the experimentally cast blades poured at the higher nominal temperature than for the experimentally cast blades poured at the lower nominal temperature.

3. Experimentally cast coarse-grain blade groups had better uniformity, similar initial failure time, but lower mean life than a group of commercially cast coarse-grain blades.

INTRODUCTION

The uniformity of life of cast alloy gas-turbine blades is generally considered unsatisfactory. This lack of uniformity results in short times to initial blade failure compared to average life and does not permit maximum use of the potential performance of the material. Since the initial failure time depends upon both mean life and uniformity, an improved initial failure time will result through improved uniformity provided that there is no offsetting decrease in average life. Studies of the effects of heat treatments upon the uniformity of life of small cast AMS 5385 gas-turbine blades (refs. 1 and 2) indicate that slight, if any, improvement is obtainable in this manner (although heat treatments have been shown to improve mean life, refs. 1 and 2). A more effective method of influencing blade-life uniformity could be through the control of blade grain size.

An investigation was conducted at the NACA Lewis laboratory with the following objectives: (a) to compare the uniformity of life and initial failure time of groups of experimentally cast AMS 5385 blades of various grain sizes (commercially cast AMS 5358 blades were used as a control); and (b) to relate individual blade life to grain size of the experimentally cast blades. Grain size was varied by casting at different pouring temperatures. All blades were aged for 24 hours at 1350° F.

Metallurgical examinations were conducted to determine (a) types of blade failures, (b) blade grain size (count), and (c) metallurgical phenomena associated with blade failure. The blade-life data were analyzed by use of statistical methods.

APPARATUS AND PROCEDURE

Blade History

Experimentally produced AMS 5385 blades having different grain sizes were supplied by N. J. Grant of M.I.T.; a description of the method used in producing these blades is given in reference 3. Additional AMS 5385 blades used in this investigation were obtained from a commercial source. The nominal compositions for all these blades, obtained from references 3 and 4, respectively, are as follows:

Type	Source	Reference	C	Mn	S	Cr	Ni	Mo	Fe	Co
A	Experimental	3	0.30	0.5	----	27.00	2.5	6	----	bal.
B	Commercial	4	0.20 to 0.35	1.00 max	1.00 max	25.00 to 29.00	1.75 to 3.75	5.00 to 6.00	2.00 max	bal.

For convenience, these experimental and commercial blades will hereinafter be referred to as type A and type B blades, respectively.

The type A blades, prior to receipt, had been designated as being either fine or coarse grained, on the basis of pouring temperature. All these blades were produced from one master heat of the alloy. In order to vary grain size, blades had been cast at two nominal pouring temperatures. One lot of blades was cast in three subheats (subsequently designated groups A_1, A_2, and A_3) with pouring temperatures in the vicinity of 2615 to 2637° F. Another lot was cast in three subheats (subsequently designated groups A_4, A_5, and A_6) with pouring temperatures about 100° F higher. These two lots were designated as fine and coarse grain, respectively.

In preparing the wheel for operation, 30 blades of each of these two initial lots were installed in the wheel. Metallographic study of the failed blades, however, revealed that the initial fine-grained group ($A_1 + A_2 + A_3$) comprised blades having grain counts from 10 to 11,200 per cross section, and that the initial coarse-grained groups ($A_4 + A_5 + A_6$) comprised blades having grain counts from 4 to 19 grains per cross section. To avoid such a large range of grain sizes within a group, the blades were regrouped according to their respective subheats, A_1, A_2, A_3, A_4, A_5, and A_6 for analysis. This is the smallest logical subgrouping, as each subheat of blades was cast at one time at a specific pouring temperature into one mold. This subdivision resulted in unequal blade groups as shown in table I. The casting temperature (ref. 3) used to produce the blades of each subheat and the grain count range for each blade subheat (group) are given in table I. All these blades had been aged for 24 hours at 1350° F prior to their receipt by the NACA.

The commercially produced blades, designated as type B, were also poured from one master heat. These blades were received in the as-cast condition and were subsequently aged 24 hours at 1350° F. The blades were aged in an electric resistance-type furnace, which was controlled to ±10° F of the desired temperature. These blades, also described in table I, were used for comparison with the experimentally cast blades.

All blades used in this investigation were radiographed and visually inspected to detect internal and external flaws, respectively. The shrouds of the blades (fig. 1) were ground to a uniform length, width, and thickness of 0.454, 0.270, and 0.050 inch, respectively, to eliminate shroud mass as a variable.

Blade Evaluation Unit

A small gas turbine supplied with hot gases from a turbojet combustion chamber was used. This apparatus is similar to that described in reference 5, but incorporated the following modification. A thin sheet of metal was placed about the turbine about 4 inches from the inner wall of the water-jacketed housing surrounding the turbine. The space between the metal sheet and the housing was filled with asbestos packing. This arrangement prevented ricocheting of failed blade fragments. The turbine operating temperatures were indicated by a thermocouple located in the inlet duct about 12 inches upstream of the turbine inlet. The wheel contained 142 blades - 90 of which were test blades - and had an over-all diameter of 12.5 inches. Long-neck and short-neck blades (fig. 1) were alternately spaced in the wheel.

2495

Turbine Operation

The turbine was operated in the following manner. Combustion air was supplied and the turbine was motored at approximately 6000 rpm for 5 minutes. Combustion was initiated and operating conditions attained in approximately 3 minutes. The wheel was operated to obtain a blade midspan stress of approximately 19,000 pounds per square inch and a temperature of approximately 1450° ±15° F. Upon blade failure, indicated by a change in pitch of sound coming from the unit, combustion was terminated, and air flow reduced to such a value that the turbine motored at about 6000 rpm. This air flow was maintained for 10 minutes in order to cool the assembly. Shutdowns were made quickly to minimize possible effects of vibration caused by wheel unbalance. The turbine wheel was then removed for replacement of failed blades. Severely cracked blades were considered failed and replaced. The wheel was balanced before initial operation, and thereafter as necessary.

Metallurgical Examination

Fracture surfaces of all failed test blades were visually examined. Transverse sections 1/8 inch thick were cut from the blades, 1/16 inch below the failure zone. Rockwell A hardness, grain size, and microstructure were determined in this section. The etchant used in determining grain size was 5 percent aqua regia with 20 to 30 milligrams of molybdic acid per 100 cubic centimeters of solution. The etchant used to bring out microstructure was 5 percent aqua regia. Both etches were applied electrolytically. The grain-size evaluation was based upon an actual count of the number of grains per cross-sectional area except in the case of the very-fine-grained blades, for which the number of grains present was determined in the following manner:

The average A.S.T.M. grain size of the cross-sectional area was determined and converted to grains per square millimeter from the grain size table in reference 6; the number of grains per blade cross section was then calculated.

RESULTS AND DISCUSSION

Metallurgical Examination

Mechanism of failure. - Metallurgical examination of the failure zones of all the blades showed that the fracture surfaces were typical of stress-rupture failures. Evidences of fatigue would not be expected in these failures since the blades had shrouds which would tend to provide greater rigidity and hence reduce vibratory stress. The initial failure zones had gray oxide films, and the final failure zones had temper oxide coloration graduating from blue to light straw. The fractures were initiated by intergranular cracks and then progressed by intergranular or transgranular paths, or both. Typical microstructures of type A and B blades before and after operation are shown in figure 2.

Heterogeneity of microstructures. - Heterogeneity of microstructure within a given blade and between blades of the same group was observed. This heterogeneity could be responsible in part for some of the blade-life variation which was observed.

Grain size. - Grain-size data are presented in tables I, II, and III. Photomicrographs illustrating the grain size and uniformity of grains for type A and B blades are shown in figure 3. It should be of great interest to note that remarkably fine grain sizes (A.S.T.M. 3 to 8, or 2100 to 11,200 grains per cross section) could be produced in a casting. Grain sizes of this magnitude have been found exceedingly difficult to obtain.

It can be seen from table II that there is considerable difference in individual grain sizes among blades from the same group, particularly in the case of the finer-grained groups A_1 and A_2. This is also seen from the standard deviation of grain count given in table III. In the case of the coarser-grained groups A_3, A_4, A_5, and A_6, there is better uniformity (i.e., smaller standard deviation) of grain size among the blades from each group.

It will be noted from table I that the finer-grained blades were produced at the lower pouring temperatures. It will also be noted that groups A_1, A_2, and A_3, which were poured at substantially the same temperature (table I), had widely varying grain sizes. As might be expected, temperature variations are more critical as regards grain-size control, when the blades are cast at low pouring temperatures (for fine-grained blades) than when they are cast at higher pouring temperatures (for coarse-grained blades). Of interest is the fact that group A_3, which was poured at 2637° F, has a grain size only slightly less than that of groups A_4, A_5, and A_6, which were poured in the range 2714° to 2736° F.

Groups A_1 and A_2, both reported as being poured at 2615° F, have grain counts of 2100 to 11,200 per cross section and 32 to 250 per cross section, respectively, probably because of actual differences in the pouring temperatures.

The casting procedure for these blades (ref. 3) and the observed relation between grain size and pouring temperature make the reported temperatures of qualitative rather than quantitative value.

2495

Hardness studies. - Reference to the Rockwell A hardness values of unused and of operated blades for each group shown in table IV indicated that age hardening occurred during operation. The hardness investigation disclosed that all groups reached the plateau of their hardness curves by the time their initial failures occurred, and that the average hardness value of this plateau is essentially the same for each group.

Comparison of performance of blade groups. - The individual times to failure for the type A blades are summarized in table II. The mean and standard deviations for blade life and grain size are given in table III. The data indicate that average life increases with increasing grain size - the coarser-grain-size groups having greater average life than the fine-grain groups A_1 and A_2.

Each of the six groups of the type A blades has been compared to the others by statistical methods to determine whether or not observed differences in performance are significant. The results of these tests are summarized in table V. It may be seen that the performance of the very fine-grained group A_1 is different from all other groups - even different from groups A_2 and A_3 that were poured in the same temperature range. The next finest group, A_2, is also different in performance from all other groups. Group A_3, however, is not different in performance from groups A_4, A_5, and A_6 that have somewhat larger grain size, even though the pouring temperature was indicated as being at least 77° F lower for group A_3. The very coarse-grain groups A_4, A_5, and A_6, which were poured at the higher temperatures, were not different in performance from one another. Since A_3 was poured at a different nominal temperature from A_4, A_5, and A_6, it probably should be considered separately from these three groups. Hence, it may be concluded that there are four grain-size groups: A_1, A_2, A_3, and $A_4 + A_5 + A_6$.

Statistical analysis of the observed differences in uniformities (standard deviation) among groups A_1, A_2, A_3, and the composite group $A_4 + A_5 + A_6$ (table V) reveals A_2 to have a different (greater) uniformity from A_1 and A_3, but not from group $A_4 + A_5 + A_6$. Group A_1 does not have a uniformity significantly different from either A_3 or $A_4 + A_5 + A_6$, and group A_3 does not have a uniformity significantly different from $A_4 + A_5 + A_6$. These results would not seem to suggest that any particular grain size range is preferable as regards blade life uniformity. Study of the grain-size standard deviations for each of these four groups does not suggest any relation between this quantity and blade life uniformity, although it might be expected from a priori considerations that the greater the grain size variation, the greater the blade life variation and that with very large grain sizes, variation might be greater because of possible orientation effects.

2495

It is of interest, to compare the life of blades poured at 2615° to 2637° F with the life of blades poured at 2714° to 2736° F (i.e., comparison of a composite of groups A_1, A_2, and A_3, with a composite of groups A_4, A_5, and A_6) to indicate whether any difference in uniformity might be expected among blades poured at different nominal temperature levels. In so doing it is found that the uniformity of the blades poured at the high temperature (coarse grained) is better than that of the blades poured at the low temperature (fine grained) (tables III and V). This might be expected because, as previously mentioned, the range of grain sizes within the combined low-pouring-temperature group ($A_1 + A_2 + A_3$) was very large (10 to 11,200 grains per cross section in table I); in addition, this group had a greater range in life than the composite coarse-grained group. It will also be noted that the composite coarse-grain group has the better mean life and initial failure time.

In a practical application, the higher pouring temperatures would probably be preferable; the differences in the mean lives of successive heats are not so great as in the case of blades poured at low temperatures; hence, the over-all uniformity of a composite group of coarse-grained blade heats would probably be better than that for fine-grained blade heats. Also, the life tends to be higher with the coarse grain size obtained at the higher pouring temperature.

Relation of blade life to grain size. - A relation between blade life and grain count may be seen from figure 4; blade life increases with grain size. For these particular data, this relation may be approximated by the curvilinear line of regression having the equation $y' = 186.5 - 10.9 \log_{10} x$, where x is number of grains per blade cross section and y' is the estimated blade life in hours. The standard deviation of residuals, a measure of variation about the line of regression (see appendix), is 6.2 hours. Hence, for all practical purposes actual blade life for a given grain count will be within ±18.6 hours of the time predicted by the equation. The index of correlation is 0.87, which may be presumed to indicate a fairly high degree of correlation. The probability is 1 percent that the index of correlation will not be less than 0.76 nor greater than 0.93. Study of figure 4 does not reveal any orientation effects. Had there been orientation effects, the scatter of blade life would be expected to be much more pronounced with coarse-grained blades than with finer-grained blades.

Comparison of uniformity of experimentally and commercially cast blades. - Study of table III reveals that the type B blades (commercial, aged 24 hr at 1350° F) have a better mean life but a considerably poorer standard deviation than the composite group $A_4 + A_5 + A_6$ (aged at 1350° F for 24 hr), although the grain sizes are of the same order of magnitude. Statistical analysis corroborates the fact that these groups are from different populations and that the standard deviations may definitely be considered different (table V).

The big difference in standard deviations for these two groups warrants consideration. It is possible that the blade arrangement in the mold for the experimentally cast blades was such as to produce a more uniform cooling rate among the blades than is the case with the commercially produced blades. The experimentally cast blades were arranged in a circular manner about sprues. It is understood that the commercial blades were arranged in a square or rectangular manner, within the mold, which would cause different cooling rates among the blades and larger variability in the as-cast structure. Metallographically it was found that the experimentally cast blades had more nearly uniform sized grains than did the commerically produced blades. It is possible that this difference is associated with the better uniformity of performance of the experimentally cast blades. The reason for the poorer mean life of the experimentally produced blades is not known but could be the result of chemistry differences and/or melting practices.

First failure times. - From table II, it is seen that best initial failure times are yielded by the coarse-grained blade groups. When the sample (group) standard deviations are corrected for sample size and the initial failure times estimated from lower population limits, it is found that initial failure time increased as average grain size of the groups increased. (Initial failure time for A_1 is less than for A_2, which is less than for A_3, A_4, A_5, and A_6; the last four groups are about equal). Initial failure times (practical engine blade life) of the coarser-grain experimentally cast groups were similar to those of the commercially cast group.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effect of pouring temperature and grain size upon the engine life of AMS 5385 gas turbine blades:

1. A correlation was found to exist between the number of grains per blade cross section and blade life for the experimentally cast blades; longer blade life was associated with the coarser grain sizes.

2. The initial failure time and uniformity of life were better for the experimentally cast blades poured at the higher nominal temperature than for the experimentally cast blades poured at the lower nominal temperature.

3. Experimentally cast coarse-grain blade groups had better uniformity of life, similar initial failure times, but lower mean life than a group of commercially cast course-grain blades.

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APPENDIX - STATISTICAL PROCEDURES

The following statistical formulas were used to evaluate the significance of observed differences in mean and standard deviation among the subject groups.

The mean life of a blade group is:

$$\bar{x} = \frac{\sum_{i}^{N} x_i}{N}$$

2495

and the standard deviation is

$$\sigma = \sqrt{\frac{\sum_{i}^{N} (\bar{x} - x_i)^2}{N}}$$

where

N total number of blades in sample

$\bar{x}$ mean life for sample, hr

x_i individual blade life, hr

σ standard deviation of blade life in sample, hr

The following test (ref. 7) may be used to determine whether there is a difference between two populations, that is, whether either or both the mean and standard deviation have changed.

$$\lambda_H = \left(\frac{\sigma_1}{\sigma_0}\right)^{N_1} \left(\frac{\sigma_2}{\sigma_0}\right)^{N_2}$$

where

$$\sigma_0^2 = \frac{N_1\sigma_1^2 + N_2\sigma_2^2}{N_1 + N_2} + \frac{N_1 N_2}{(N_1 + N_2)^2} (\bar{x}_1 - \bar{x}_2)^2$$

and

N_1 number of items in first group

N_2 number of items in second group

$\bar{x}_1$ mean life of first group

$\bar{x}_2$ mean life of second group

λ_H a sampling distribution from which the significance of a difference between populations is obtained

σ_0 standard deviation of the two groups combined

σ_1 standard deviation of first group

σ_2 standard deviation of second group

2495

The interpretation of the value of λ_H may be obtained from table 48 of reference 7 (p. 415).

The following test may be used to determine whether or not an observed difference between two standard deviations has any significance.

$$F = \frac{\sigma_1^2 \dfrac{N_1}{N_1 - 1}}{\sigma_2^2 \dfrac{N_2}{N_2 - 1}}$$

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F a sampling distribution from which the significance of a difference between standard deviations is obtained

The interpretation of the value of F may be obtained from table IX of reference 7 (p. 476).

In the use of the preceding tests, it has been assumed that the distribution of blade failures is normal.

The curvilinear regression fitted to the plot of blade life versus the logarithm of the number of grains per blade cross section was determined by the method of least squares (ref. 8). The standard error of estimate S of the regression line is

$$S^2_{y \cdot f(x)} = \frac{\Sigma(z'')^2}{n} = (\sigma_{z''})^2$$

where

z" difference between observed blade life and estimated blade life corresponding to given grain size

n number of blades in group

The index of correlation $\rho_{y \cdot x}$ is defined by

$$\rho_{y \cdot x} = \frac{\sigma_{y''}}{\sigma_y}$$

2495

where

$\sigma_{y''}$ standard deviation of estimated lives about mean life

σ_y standard deviation of observed lives about mean life

The reliability of the index of correlation is computed as follows (ref. 7, pp. 300 - 301).

The value of r_{12} (which corresponds to $\rho_{y.x}$ of ref. 8) is transformed to z_{12}, by the equation $z_{12} = \tanh^{-1} r_{12}$. The sampling distribution of z_{12} has a practically normal distribution with a standard deviation approximating

$$\sigma_z = \frac{1}{\sqrt{N - 3}}$$

where

N number of items in group

The upper and lower limits of z_{12} for a given probability are computed using

$$z_{12} \pm (t) \frac{1}{\sqrt{N - 3}}$$

where

t is number of standard deviations corresponding to desired probability. The values of z are then converted back to values of r, thus

$$r_{upper} = \tanh z_{upper}$$

$$r_{lower} = \tanh z_{lower}$$

From the values of z_{upper} and z_{lower}, the limiting values of the index of correlation may be obtained.

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TABLE I. - BLADE GROUP HISTORY

Group[a]	Metal pouring temperature[b], °F	Mold temperature[b], °F	Range of grains per cross section	Average number of grains per blade cross section	Number of blades in group	Heat treatment remarks
A_1	2615	1500	2100-11,200	5800	11	Aged 1350° F for 24 hr
A_2	2615	1500	32-250	103	14	Aged 1350° F for 24 hr
A_3	2637	1500	10-60	29	5	Aged 1350° F for 24 hr
A_4	2714	1500	7-19	13	13	Aged 1350° F for 24 hr
A_5	2721	1500	7-13	10	11	Aged 1350° F for 24 hr
A_6	2736	1500	4-14	8	6	Aged 1350° F for 24 hr
$A_1+A_2+A_3$	----	----	10-11,200	2200	30	All blades from groups 1, 2, and 3
$A_4+A_5+A_6$	----	----	4-19	11	30	All blades from groups 4, 5, and 6
B	----	----	2-13	6	30	Aged 1350° F for 24 hr

[a]Group B obtained from commercial source and from one heat; the blades of the remaining groups were obtained from N.J. Grant of M.I.T. and were also from one heat.

[b]Data obtained from reference 3.

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TABLE II. - SUMMARY OF INDIVIDUAL BLADE FAILURE TIMES AND GRAIN COUNTS FOR EACH GROUP

Group	Number of grains per cross-sectional area	Time to failure, hr
A_1	8,400	130.2
	11,200	139.8
	5,600	141.3
	4,300	141.9
	11,200	141.9
	2,100	143.6
	4,300	146.2
	4,300	147.9
	5,600	149.6
	4,300	159.6
	2,800	159.6
	$\bar{x}$=5,800	$\bar{x}$=145.6
	σ=3,000	σ= 8.2
A_2	150	152.5
	185	159.6
	140	161.6
	60	164.6
	185	165.3
	250	165.3
	95	166.2
	46	167.2
	49	168.7
	60	169.1
	32	169.1
	75	169.1
	60	169.5
	55	169.5
	$\bar{x}$=103	$\bar{x}$=165.5
	σ= 65	σ= 4.7
A_3	36	168.4
	17	170.8
	60	172.9
	10	184.1
	22	189.0
	$\bar{x}$=29	$\bar{x}$=177.0
	σ=18	σ= 8.0
A_4	8	168.2
	14	169.5
	9	169.5
	7	170.8
	18	170.8
	18	170.8
	16	176.3
	13	176.3
	19	176.3
	8	180.0
	12	182.8
	9	185.6
	12	186.9
	$\bar{x}$=13	$\bar{x}$=175.7
	σ= 4	σ= 6.1
A_5	7	167.2
	7	168.2
	8	170.8
	13	170.8
	11	172.2
	8	172.9
	13	173.2
	13	180.0
	11	181.2
	8	181.8
	12	186.9
	$\bar{x}$=10	$\bar{x}$=175.0
	σ= 2	σ= 6.1
A_6	8	169.1
	10	169.5
	7	172.9
	7	172.9
	14	172.9
	4	177.8
	$\bar{x}$= 8	$\bar{x}$=172.5
	σ= 3	σ= 2.7
B	5	164.6
	5	165.6
	(a)	170.8
	9	172.2
	5	177.8
	8	177.8
	5	180.0
	5	181.2
	7	182.8
	6	184.1
	2	185.6
	4	186.9
	3	186.9
	9	186.9
	5	186.9
	4	189.0
	4	189.0
	3	191.2
	2	191.2
	6	194.9
	5	196.5
	4	197.4
	13	222.2
	11	224.4
	9	228.1
	9	228.1
	5	228.1
	4	230.3
	2	251.3
	4	253.0
	$\bar{x}$= 6	$\bar{x}$=196.8
	σ= 3	σ= 23.9

[a]Blade was misplaced after failure prior to grain size determination.

TABLE III. - SUMMARY OF STATISTICAL DATA

Group	Blade life		Grain size mean, $\overline{x}$	Standard deviation of number of grains per cross-section, σ
	Sample mean, $\overline{x}$, hr	Sample standard deviation, σ, hr		
A_1	145.6	8.2	5800	3000
A_2	165.5	4.7	103	65
A_3	177.0	8.0	29	18
A_4	175.7	6.1	13	5
A_5	175.0	6.1	10	2
A_6	172.5	2.7	8	3
$A_1+A_2+A_3$	160.1	13.5	2200	3300
$A_4+A_5+A_6$	174.8	5.9	11	4
B	196.8	23.9	6	3

2495

TABLE IV. - SUMMARY OF HARDNESS DETERMINATIONS

Group	Average Rockwell A hardness	
	Aged[a]	After failure[b]
A_1	67	71.7
A_2	67	72.2
A_3	67	72.6
A_4	67	72.4
A_5	67	72.6
A_6	67	72.2
B	69.7	73.7

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[a]Average of five readings, before test.

[b]Average of all blades in a group.

TABLE V. - SUMMARY OF STATISTICAL ANALYSIS OF BLADE LIVES TO DETERMINE WHETHER GROUPS DIFFER SIGNIFICANTLY FROM EACH OTHER

[Based on "λ_H" test at the 0.01 level of significance.]

	A_1	A_2	A_3	A_4	A_5	A_6	$A_4+A_5+A_6$	$A_1+A_2+A_3$
A_2	Y[b]							
A_3	Y[c]	Y[b]						
A_4	Y	Y	N					
A_5	Y	Y	N	N				
A_6	Y	Y	N	N	N			
$A_4+A_5+A_6$	Y[c]	Y[c]	N[c]					
$A_1+A_2+A_3$							Y[a]	
B							Y[a]	

[a]"F" test shows significant difference in standard deviations, at 0.01 level.

[b]"F" test shows significant difference in standard deviations, at 0.05 level.

[c]"F" test shows no significant difference in standard deviations, at 0.05 level.

Note: To compare any two groups, select the block that is common to both. The Y found in the block means that the groups compared are different on the basis of the λ_H test. The N found in the block means that the groups are not considered different, based on the λ_H test. The superscript refers to the significance of the differences in standard deviations based upon the "F" test.

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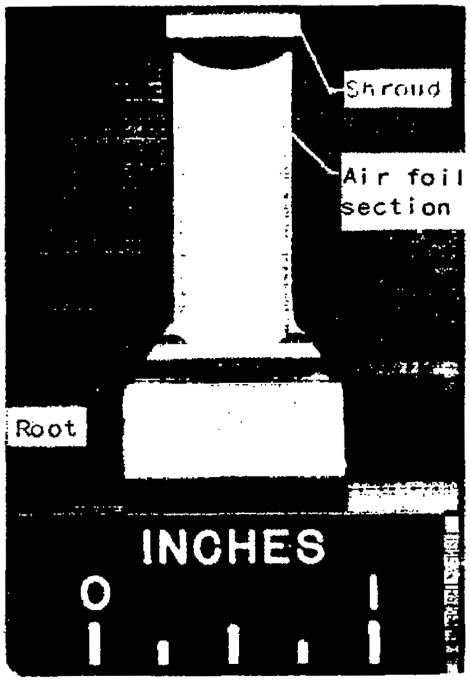
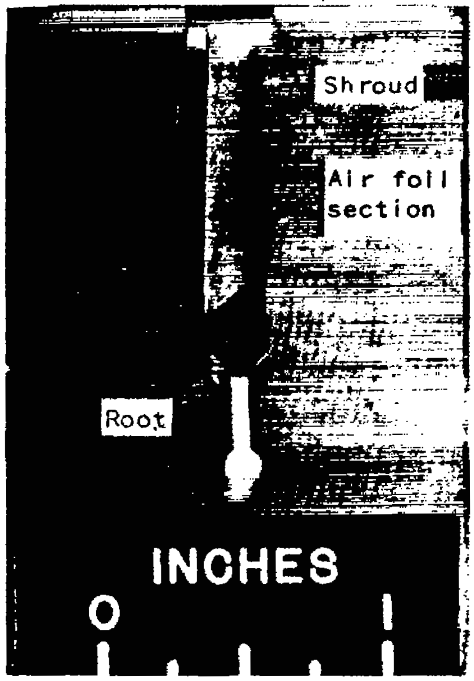
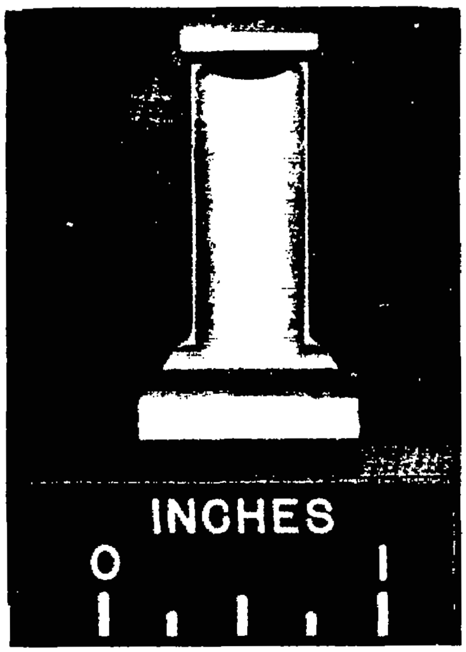


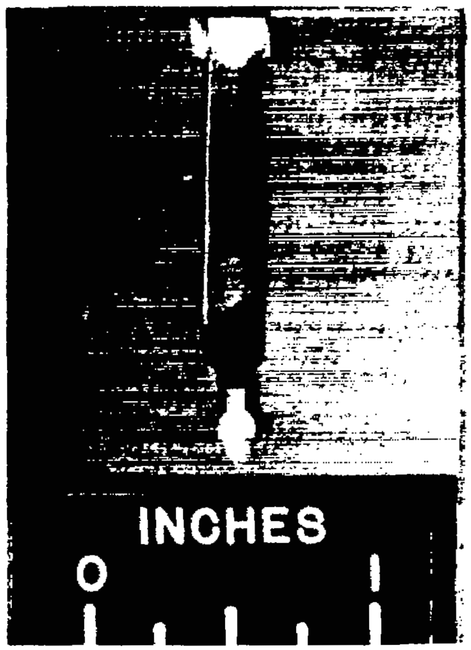
(a) Long-necked turbine blade, front view.



(b) Long-necked turbine blade, side view.



(c) Short-necked turbine blade, front view.



(d) Short-necked turbine blade, side view.

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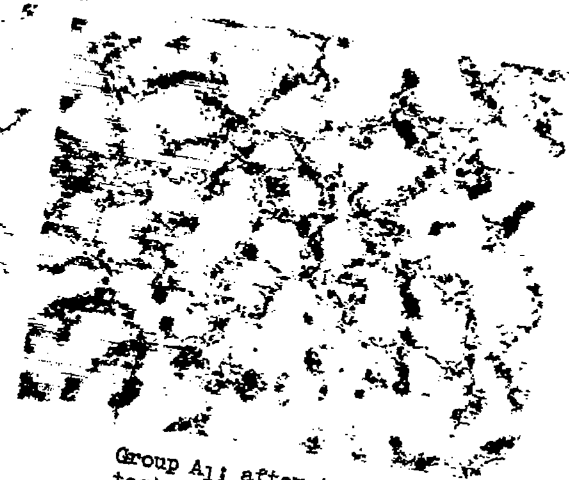
Figure 1. - Typical gas-turbine blades used in investigation, shown as received.

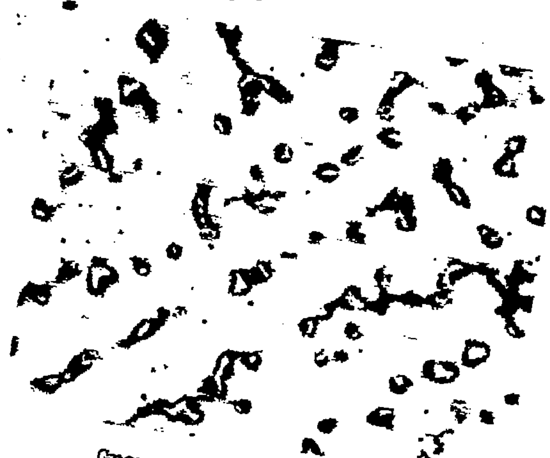
Group A_1; before operation; aged 24 hours at 1350° F.



Group A_1; after test; test temperature, 1450° F.

Typical of all fine-grain groups.

Group B; before operation; aged 24 hours at 1350° F.



Group B; after test; test temperature, 1450° F.

Typical of all coarse-grain groups.

Figure 2. - Comparison of microstructures at X250.

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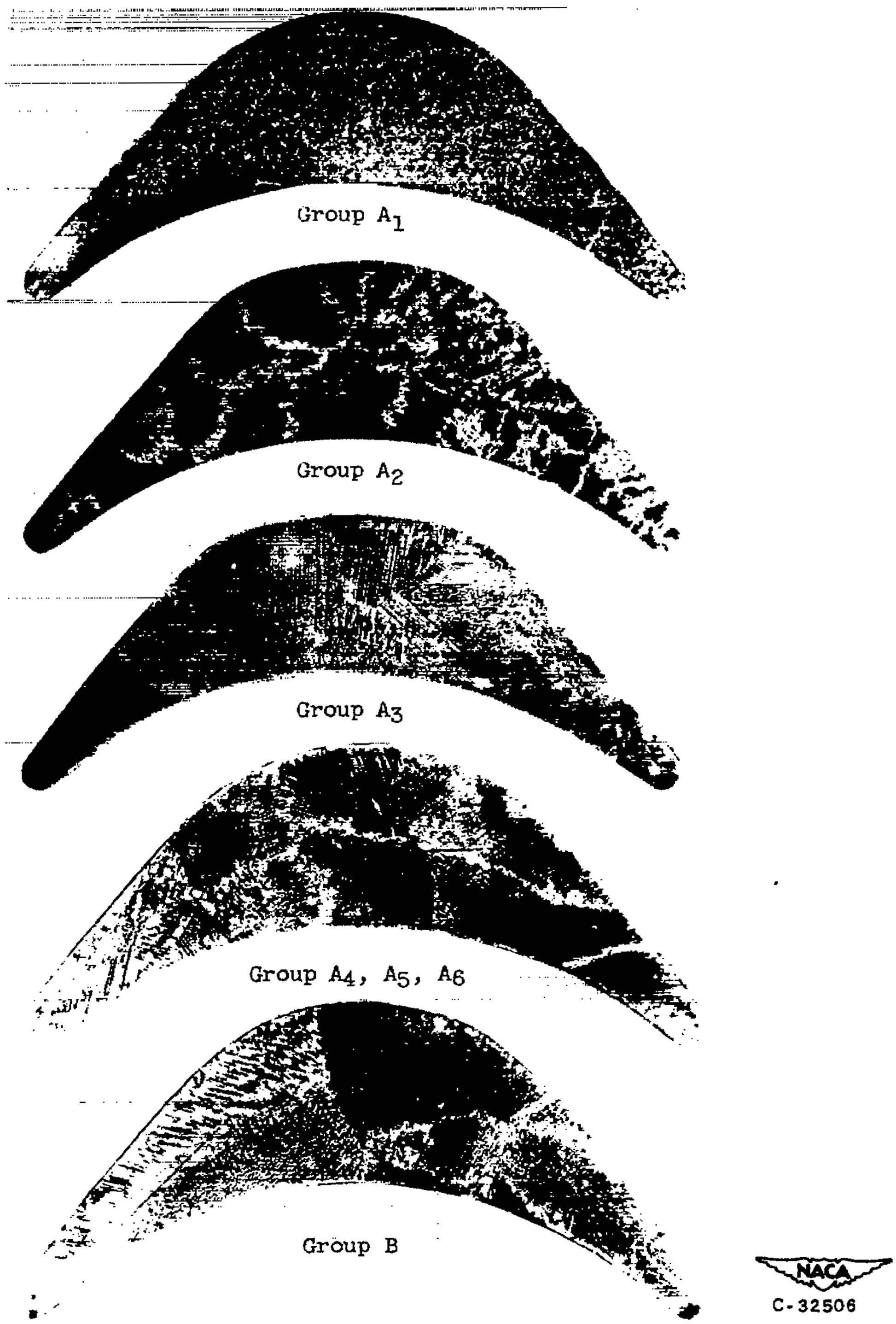

Figure 3. - Comparison of grain sizes at X10.

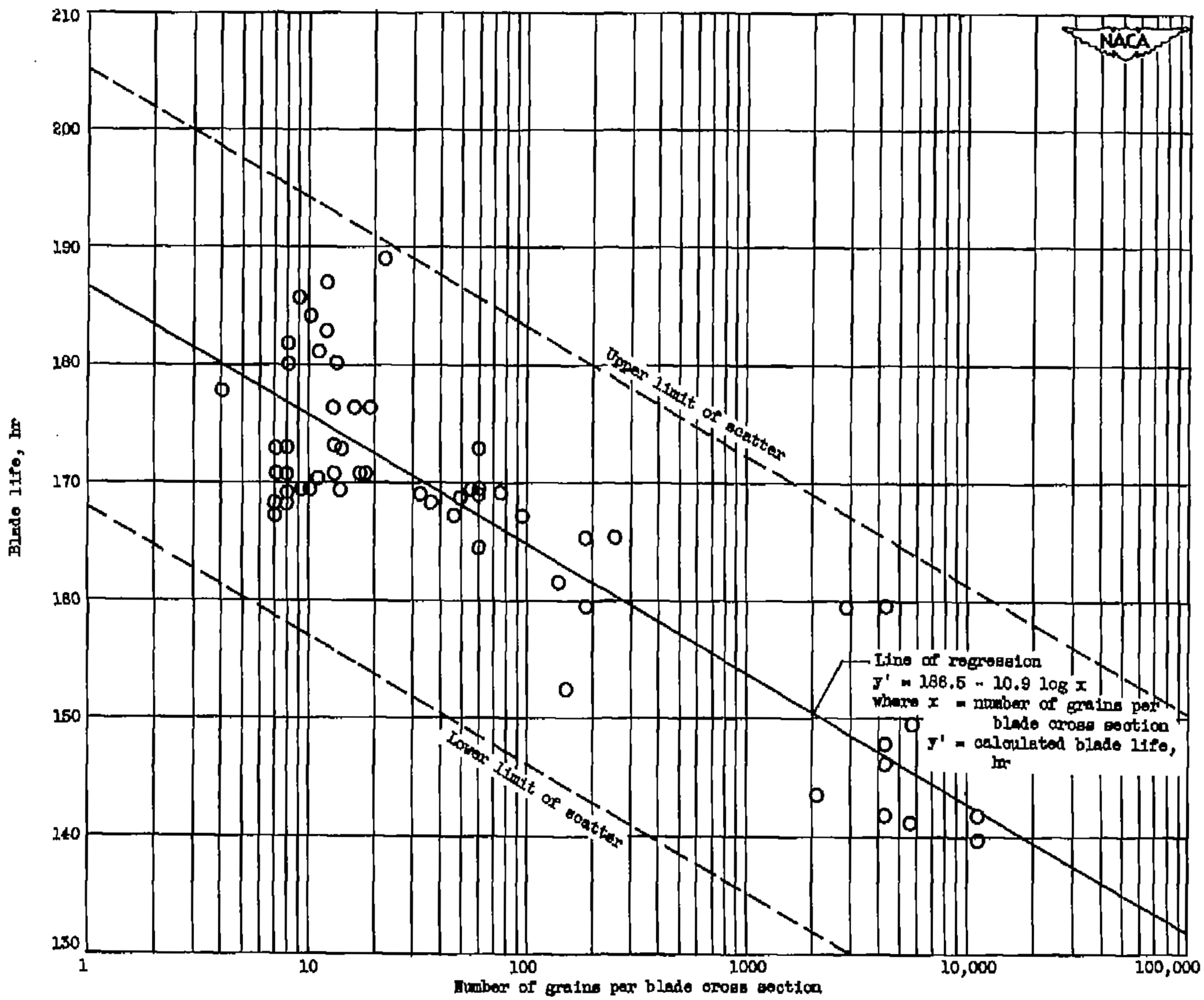

Figure 4. - Correlation between blade life and number of grains per blade cross section for experimental blades. Index of correlation, 0.87; standard error of estimate, 6.2 hours.